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Monitoring buried infrastructure deformation using acoustic emissions

Helen J Heather-Smith, Alister Smith, Neil Dixon, James A Flint and James Wordingham
Loughborough University, UK, h.heather-smith@lboro.ac.uk

Abstract

Deformation of soil bodies and buried infrastructure elements (i.e. soil-structure systems) generates acoustic emission (AE). Detecting this AE by coupling sensors to buried structural elements can provide information on asset condition and early warning of accelerating deformation behaviour. A novel approach for deformation monitoring of buried steel infrastructure (e.g. pipes and pile foundations) using AE is described in the paper. The monitoring concept employs pre-existing, or newly built, buried steel infrastructure assets as waveguides. The propagation of AE through example pipes acting as waveguides has been modelled computationally using the program Disperse. A parametric study has been used to investigate the influence of key variables such as burial depth, surrounding soil type, internal environment, pipe diameter, wall thickness, frequency and mode type upon AE propagation and attenuation. Understanding the propagation and attenuation of AE is of fundamental importance for development of a monitoring strategy and specifically to determine the spacing of sensors deployed along infrastructure elements. The generation of AE due to soil-structure interaction mechanisms has been investigated using a programme of large direct shear tests of soil against steel plates under a range of conditions (e.g. soil type, plate surface conditions, stress level, strain rate). New, fundamental understanding of AE generation and propagation in buried infrastructure is enabling a framework to be developed for interpreting asset condition from AE measurements. The paper will introduce the approach developed, describe the parametric study of AE propagation and attenuation presenting example results, and show typical AE behaviour for soil-structure interaction obtained in the large shear tests. The implications for design of a monitoring framework will be discussed.

1. Introduction

Acoustic emissions (AE) are elastic stress waves generated by the rapid release of energy, which are then radiated away from the source (1). Deformation of soil bodies and buried infrastructure elements (i.e. soil-structure systems) such as pipes and foundations generate measurable AE. This is a result of frictional interactions between soil particles and the structural interface. Monitoring and interpreting the AE by coupling sensors to buried structural elements can provide information on asset condition as well as early warnings of accelerating deformation behaviour (2).

AE is widely used in many industries for non-destructive testing and evaluation (e.g. for the detection of defects and leaks in pipe networks and pressure vessels). However, the application of AE in geotechnical engineering has not been widespread. Recent research has developed an AE early warning system for slope instability, which has demonstrated that AE can be used to monitor soils and soil-structure systems and provide quantitative information on their deformation behaviour (3, 4, 5, 6, 7, 8). This research has demonstrated the vast potential that AE has in monitoring geotechnical infrastructure.

This paper presents a novel approach for deformation monitoring of buried infrastructure using AE, which employs pre-existing, or newly built, buried steel infrastructure assets as waveguides. The study objectives were to enhance understanding of: (a) the propagation and attenuation of AE through buried infrastructure, which is of fundamental importance for the development of a monitoring strategy, and specifically to determine the spacing of sensors along infrastructure elements; and (b) the generation of AE due to soil structure interaction mechanisms that will enable asset behaviour to be interpreted from the measured AE.

This paper introduces the monitoring approach developed, describes a parametric study of AE propagation and attenuation presenting example results, and shows typical AE behaviour for soil-structure interactions obtained from large shear box tests. The implications for design of a monitoring framework (Figure 1) are also discussed briefly.

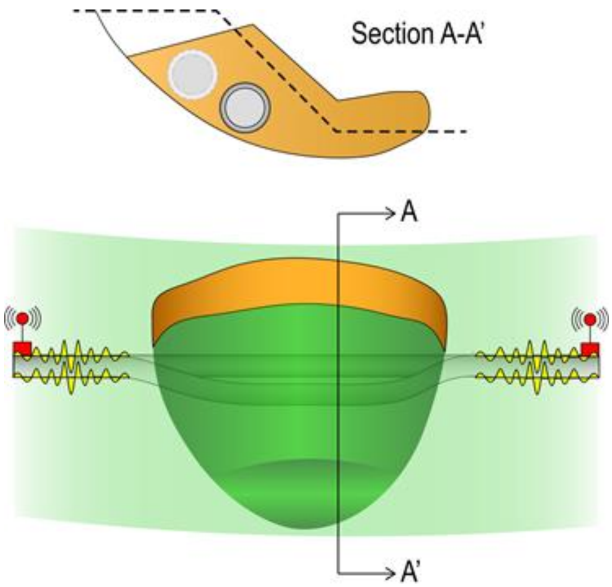

Figure 1. AE monitoring concept for buried infrastructure. This example shows deformation of a buried pipe due to a landslide. AE generated by soil-structure interaction propagate as guided waves along the pipe to the monitoring sensors.

2. Methodology

The generation, propagation and attenuation behaviours of AE have been investigated through a combination of computer modelling with the program Disperse (9) and laboratory experiments including pencil lead break tests and element tests using large direct shear box apparatus. Using a combination of methods means comparisons and validations may be made.

Disperse is an interactive windows program designed to generate dispersion curve solutions (10). The program uses partial wave theory and global matrix methods, iterating through wavenumber, frequency and attenuation space (11) dependent on the application. AE propagation and attenuation in buried steel structures is influenced by numerous variables (Figure 2) including: burial depth, surrounding soil type, internal environment, pipe diameter, wall thickness, frequency and mode type. Disperse allows for individual variables to be changed systematically and can run multiple models quickly. A systematic and parametric study of these factors could therefore be performed with the program.

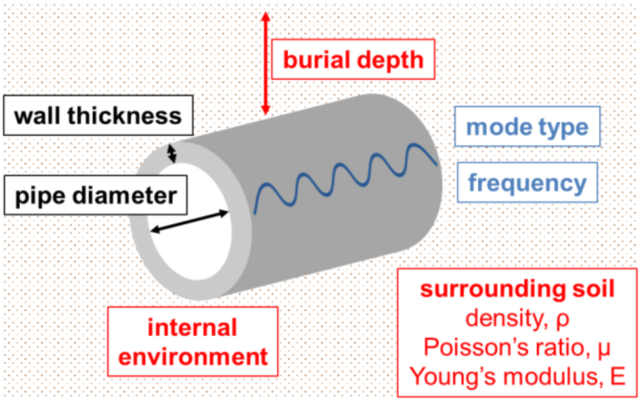

Figure 2. Variables influencing AE propagation and attenuation in buried pipes. Red labels represent environmental influences, black structural and blue wave properties.

To compare and validate the results of computer modelling, pencil lead break laboratory tests were also conducted. Pencil lead break tests generate controlled and repeatable waveforms that produce AE within a frequency range comparable to soil-soil and soil-steel interactions (confirmed through experiments conducted by the researcher). The tests were consequently used to experimentally investigate the propagation and attenuation of AE in real shell structures with a small range of mechanical properties.

To investigate AE generation, element tests of interface shear between steel plates and granular media have been performed using large direct shear apparatus (Wille Geotechnik, ADS-300). An on-going programme of tests is investigating the influence of soil type, relative density, stress level and shear rate to develop an approach to interpret AE generated by different mechanisms and the behaviours experienced by soil-structure systems.

The programme of large direct-shear tests used an AE data acquisition system as shown in Figure 3. The system comprises a piezoelectric transducer (MISTRAS R3α coupled to a structural element with silicon grease) to convert mechanical AE to a voltage, amplification to improve the signal-to-noise ratio using a pre-amplifier (0-1200 kHz filter) and main amplifier (10-100 kHz filter), an analogue-to-digital convertor, and a LabView program to process the conditioned AE. The R3α transducer was selected because of its sensitivity (30kHz resonant frequency) within the frequency range of interest (10-100kHz, explained in more detail below). Moreover, an investigation was conducted to compare the response, within this frequency range, of multiple transducers and the R3α was found to be the most sensitive and repeatable.

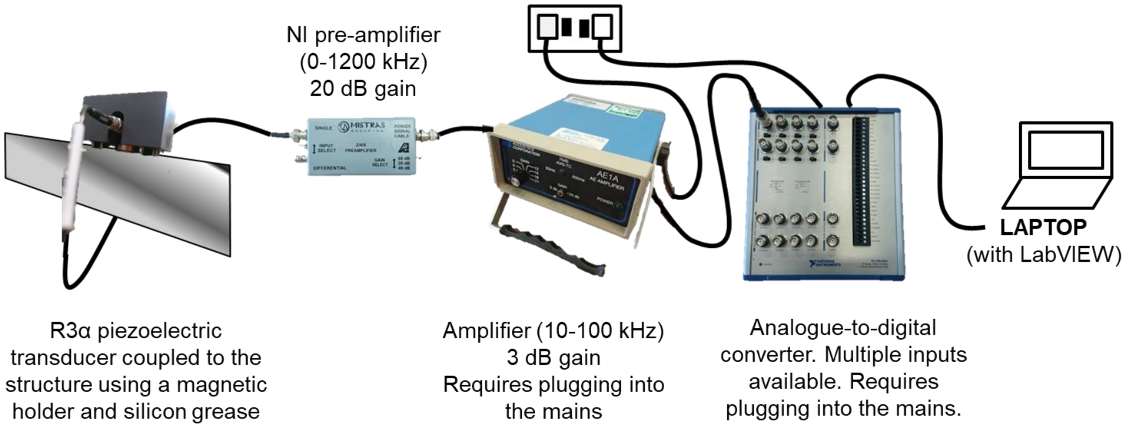

Figure 3. The AE data acquisition system used for all experiments.

Research has shown that significant AE is generated by the deformation of soil bodies and soil-structure systems within the frequency range of 10-100 kHz (12, 13, 14, 15, 16). Filtering signals below 10 kHz removes low frequency and extraneous noise (e.g. construction activity, traffic and environmental noise), which is essential for field instrumentation to reduce false alarms. Continuous monitoring at frequencies above 100 kHz requires significant processing, storage and power, which is impractical for portable, battery-operated field instrumentation. Hence, the 10-100 kHz range has been selected for the research to ensure that the results are applicable to a field-based system that can continuously measure soil-soil and soil-structure generated AE.

3. AE propagation and attenuation

A parametric study using Disperse has been conducted to investigate the influences of: wall thickness, shell radius, burial depth, surrounding soil type, internal environment, frequency and mode type, on the propagation and attenuation of AE in buried shell structures. All the models have been computed with a tri-layer system consisting of: a free internal environment – 5 mm thick steel plate (unless otherwise stated) – and soil external environment. The mechanical properties of steel were kept constant throughout the study with: density (ρ) = 7.932 g/cm^3, Poisson's Ratio (ν) = 0.287 and Young's modulus (E) = 216.906 GPa; these are the default properties of steel in Disperse. Unless otherwise stated soil is here defined by the material parameters ρ = 1.8 g/cm^3, ν = 0.3 and E = 0.12 GPa to represent a granular soil.

3.1 Influence of plate thickness

The influence of wall thickness has been investigated by modelling the structural element as a plate instead of a cylinder (to represent a shell structure). By modelling a plate rather than cylinder, the effects the radius may have on the results are removed. This approach is justified because multiple simulations have been run on tri-layer systems modelled both as a plate and a pipe with comparable attenuation behaviour results being generated. Where applicable, all further results have therefore been modelled in the same way.

Figure 4 shows how attenuation of the fundamental symmetric (S) and asymmetric (A) Lamb wave modes vary with plate thickness. The plot at the top of Figure 4 shows that as plate thickness increases the attenuation decreases at a decreasing rate. This is an inverse relationship and is shown in the bottom left figure where, arbitrarily, local maxima (n) and minima (m) have been used to plot the figure and show the $y = n/x$ and $y=m/x$ relationships. Given these relationship, the effect of plate thickness may be completely removed by plotting modelled results as a thickness product. The bottom right figure therefore shows how attenuation varies with frequency generally for a tri-layer free-steel-soil environment, irrespective of steel thickness.

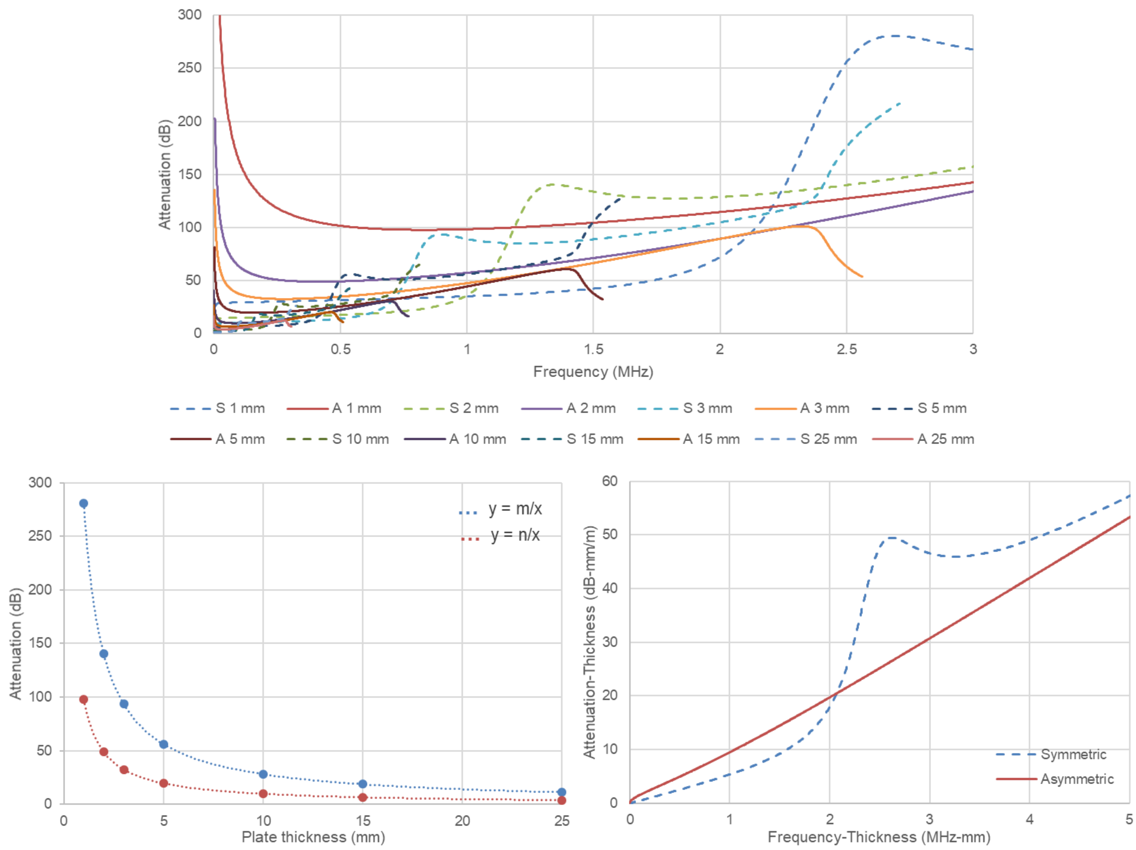

Figure 4. The relation between attenuation and plate thickness. Wave attenuation behaviours with different plate thicknesses (top), example inverse relationships between plate thickness and attenuation (bottom left), and a attenuation-thickness vs. frequency-thickness plot for a free-steel-soil system (bottom right). Behaviours modelled computationally with Disperse.

3.2 Influence of shell radius

From the figure it may be seen that the attenuation behaviours of symmetric and asymmetric attenuation with shell radius differ considerably. However, the values of attenuation for the symmetric and asymmetric waves each generally remain the same for all the modelled radii, with only negligible change. This suggests that both symmetric and asymmetric wave attenuation is largely independent of cylinder radius.

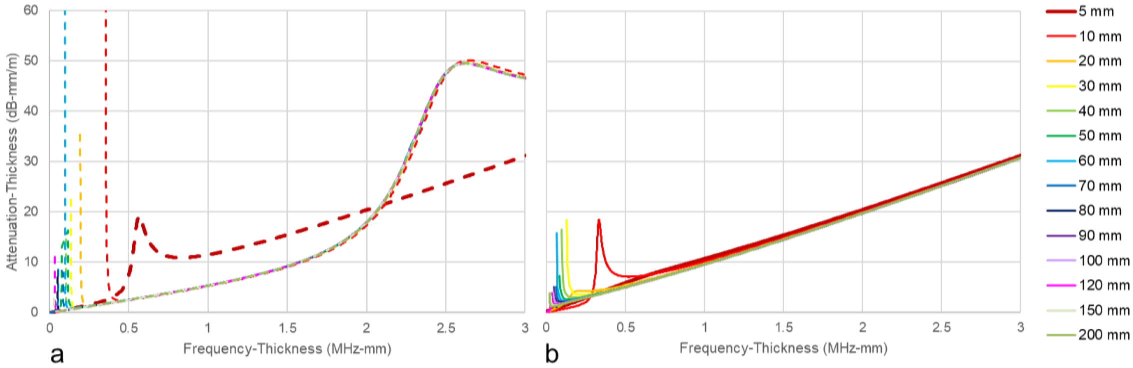

Figure 5. Attenuation behaviour with cylinder radius. Symmetric (left) and asymmetric (right) wave attenuation behaviours modelled computationally with Disperse.

For symmetric waves (Figure 5, left), attenuation is non-linear, increasing at an increasing rate with an increasing frequency-thickness. This is the case for all the modelled radii, except 5 mm. At a radius of 5 mm the modelled symmetric wave attenuation is almost equivalent to the asymmetric wave attenuation.

The attenuation of asymmetric waves (Figure 5, right) increases linearly with increasing frequency-thickness for all modelled pipe radii. This linear increase may be described by equation 1, with an R^2 value of 0.9998.

$$y = 11.1x - 2 \tag{1}$$

3.3 Influence of burial depth and surrounding soil

The influence of burial depth and the surrounding soil (external environment) have been investigated together by changing the three mechanical properties, ρ, ν and E, for the surrounding soil in the tri-layer system previously described. The parameters were investigated systematically by producing multiple models. Figures 6, 7 and 8 show the results of these investigations. These relationships describing attenuation behaviour are needed to inform design of a monitoring framework. In each study, all other parameters have been kept constant at ρ = 1.8 g/cm3, ν = 0.3 and E = 0.12 GPa.

It may be seen that the results of the studies show very similar attenuation behaviour for the fundamental symmetric and asymmetric Lamb waves. This is because the parameters and their effect on attenuation are inter-related. The results are also very similar in form and behaviour to those acquired by other authors studying the effect of external environments (11, 17).

Attenuation resulting from the external environment is controlled by extrinsic attenuation mechanisms and most notably wave coupling. Wave coupling is where wave energy leaks into and travels through two or more adjacent materials. It is dictated by the characteristic acoustic impedance (z) between the materials, in this case the steel asset and surrounding soil, where $z = \rho c$ with c being wave velocity (a function of the materials stiffness moduli and density). z may then be used to calculate reflection and transmission coefficients at half-space boundaries.

z is heavily influenced by material properties, specifically density and the related stiffness moduli. Consequently, as materials become more closely matched in properties the impedance mismatch becomes smaller and there is thus more coupling potential, leading to greater attenuation.

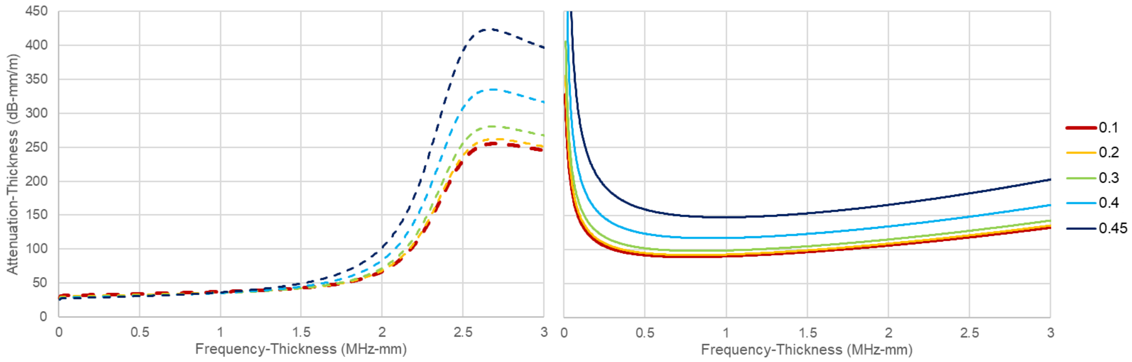

Figure 6. Attenuation behaviour for a changing soil Poisson's ratio. Symmetric (left) and asymmetric (right) wave attenuation behaviours modelled computationally with Disperse. Legend refers to Poisson's ratio values.

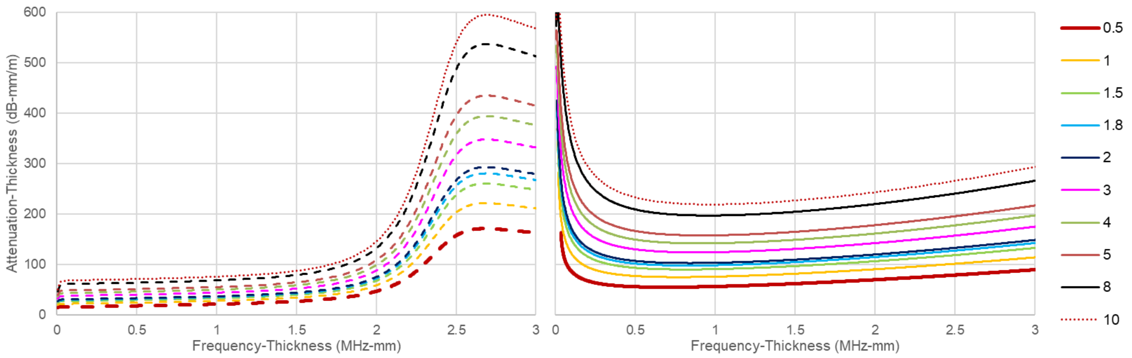

Figure 7. Attenuation behaviour for a changing soil density. Symmetric (left) and asymmetric (right) wave attenuation behaviours modelled computationally with Disperse. Legend refers to density values in g/cm3.

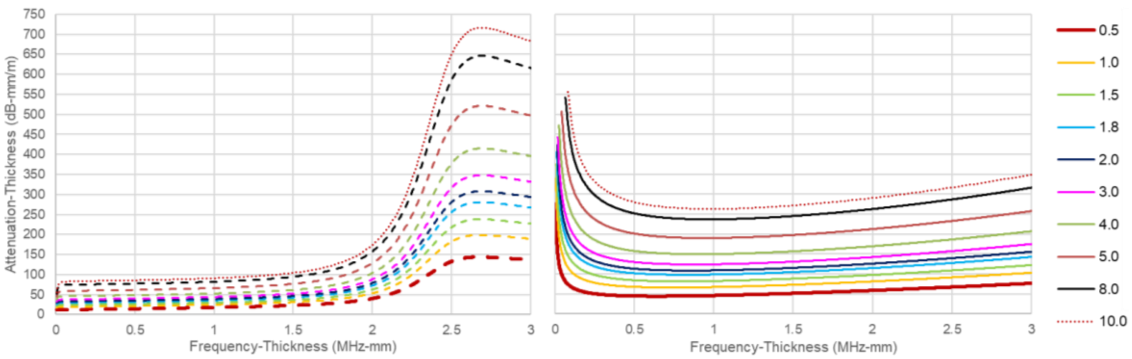

Figure 8. Attenuation behaviour for a changing soil Young's modulus. Symmetric (left) and asymmetric (right) wave attenuation behaviours modelled computationally with Disperse. Legend refers to Young's modulus values in MPa.

4. AE generation

The generation and characteristics of AE due to soil-structure interaction mechanisms are being investigated using a programme of large direct-shear tests (Figure 9). A range of soils with different properties are being sheared against steel plates (3 mm thick) under a range of conditions defined by relative density, stress level and shear rate. Table 1 shows the properties of the soil employed in the experiments reported here.

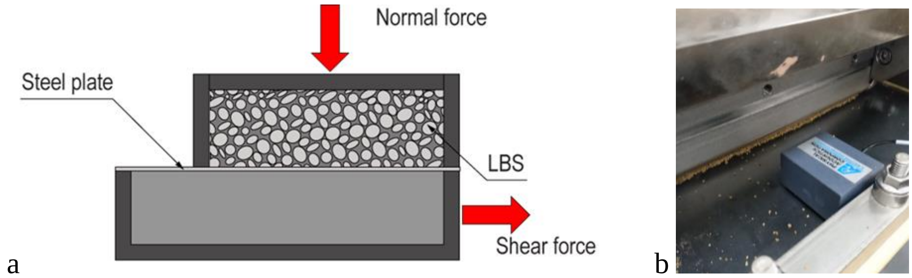

Figure 9. (a) Schematic cross-section of the large direct-shear apparatus, showing Leighton Buzzard sand (LBS) shearing against a steel plate. (b) Photograph showing the transducer connected to the steel plate.

Table 1. Properties of the LBS used for testing.

	Leighton Buzzard sand (LBS)
Minimum dry density (Mg/^{3})	1.57
Maximum dry density (Mg/m^3)	1.72
Specific gravity	2.63
Minimum void radio	0.529
Maximum void ratio	0.676
Roundness (Wadell's)	0.51
Sphericity (width-length)	0.68
Coefficient of uniformity	2.0

Figure 10 shows example results for a large direct-shear test on a Leighton Buzzard sand (LBS)-steel plate interface. The LBS was compacted and a normal stress of 150 kPa was applied, which was kept constant throughout shearing. Shear was then applied at 1 mm/minute to a total shear displacement of 40 mm.

AE time series are presented using two parameters: ring-down count (RDC) rate and root-mean-square (RMS) rate. RDC rates are the number of voltage threshold level crossings per unit time, and RMS is the cumulative rectified waveform voltage per unit time. Both parameters are indicative of the energy generated (i.e. the area under the AE waveform) per unit time.

Figure 10a shows the shear stress and RDC rate vs. shear displacement relationships, Figure 10b shows the shear stress and RMS rate vs. shear displacement relationships, and Figure 10c shows the vertical displacement vs. shear displacement relationship.

Shear resistance is gradually mobilised and reaches a peak value at approximately 2.5mm of shear displacement. During this mobilisation phase, soil contraction (i.e. negative volume change) occurs, which is evident from Figure 10c, and shear stress and AE rate (RDC and RMS) increase linearly with shear displacement. This shear stress vs. shear displacement behaviour is characteristic of interface shear between steel and granular media (e.g. 18).

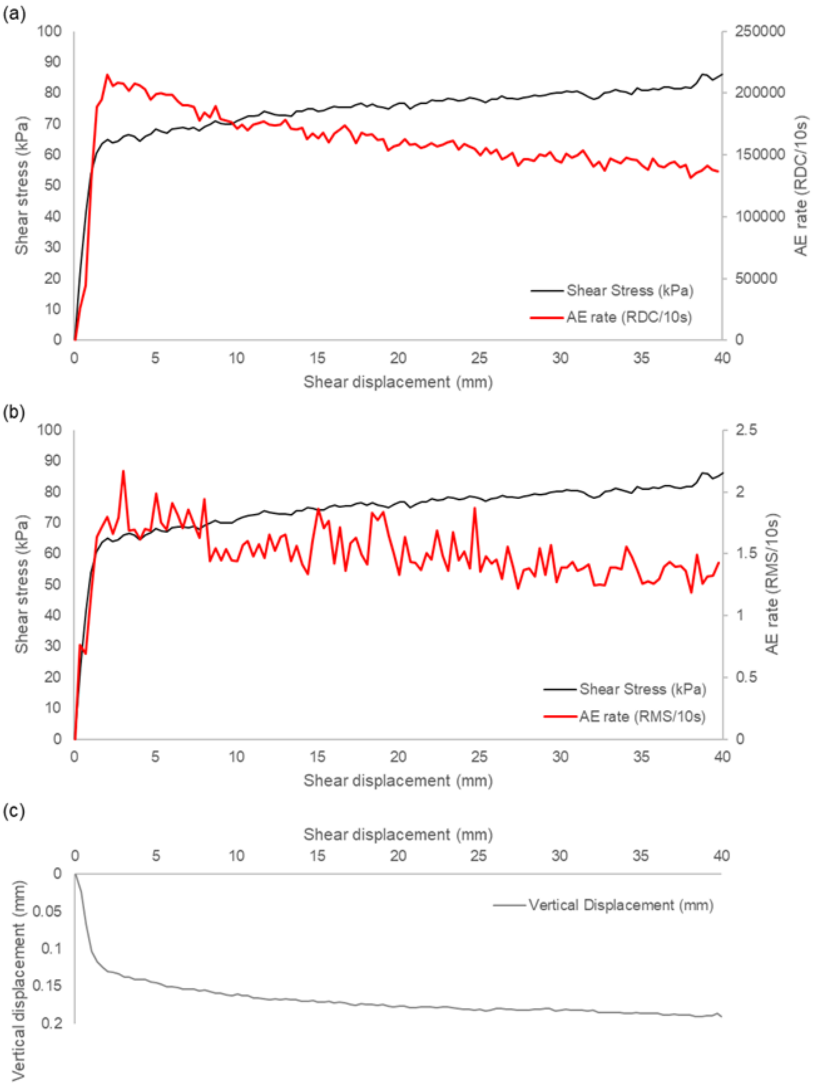

Figure 10. Results from large direct-shear tests with Leighton Buzzard sand with a normal stress of 150 kPa.

After the peak shear strength is mobilised, a transition in behaviour occurs and further shear displacement results in a small, gradual increase in shear strength. This further increase in shear stress with shear displacement is hypothesised to be due to extrusion of the LBS through the gap between the top box and the steel plate (e.g. shown in Figure 9b). This post-peak-strength shear stress behaviour contrasts with what happens to the AE rate behaviour, which reduces (both RDC and RMS) with further shear displacement. This gradual reduction in AE rates with shear displacement is hypothesised to be due to reduced roughness of the steel surface as the soil moves further over an already sheared interface.

AE is generated by deformation of soil-steel systems through the following mechanisms: inter-particle friction adjacent to the steel; friction at the interface between the steel and granular media; force chain buckling (e.g. slip-stick behaviour as interlock is overcome and regained) of particle assemblies; and degradation of particle asperities (3, 5, 6, 16). The RDC and RMS measurements both exhibit spikes in behaviour, which is caused by slip-stick between particle assemblies. The RDC rate measurements are markedly smoother than the RMS rate measurements and this is due to the difference in how they are measured: RDC only detects AE that passes above the voltage threshold level, whereas RMS measurements include all AE within the frequency range.

The significance of the results shown in Figure 10 is that AE can be used to measure pre- and post-peak strength behaviour, which is critical for health monitoring of geotechnical infrastructure. When peak strength has been mobilised, accelerating deformation behaviour takes place, which can have catastrophic consequences. Other research (3, 4, 5, 6, 7, 8) has shown that AE rates increase with increasing rates of deformation, and the influence of shear rate is currently being investigated as part of this research using the large direct-shear apparatus.

5. Developing a monitoring framework

The monitoring concept employs pre-existing, or newly built, buried steel infrastructure assets as waveguides (Figure 1). This may include: utility pipes; rock bolts; soil nails and foundations. Current focus has however been on buried steel shell structures (e.g. pipes and piles).

Developing new understanding of AE propagation and attenuation through buried infrastructure, and AE generated by soil-structure interaction mechanisms, is enabling a monitoring framework to be developed to: select sensor spacings needed to provide sufficient spatial resolution, interpret the measured AE incorporating the influence of attenuation as it propagates to the sensor location(s), and facilitate source location to enable targeted interventions.

The first step in developing the framework is production of a flow diagram, with empirical relationships computed using Disperse, linked to each step in the process which will enable users to select sensor spacings for each installation. The overall aim is then to incorporate the research findings in an algorithm for automated interpretation of AE and source location, which will enable real-time condition appraisal and early warning of deterioration, and targeted interventions.

6. Conclusions

Deformation of soil bodies and buried infrastructure elements (i.e. soil-structure systems) generates acoustic emission (AE). Detecting this AE by coupling sensors to buried structural elements can provide information on asset condition and early warning of accelerating deformation behaviour. A novel approach for deformation monitoring of buried steel infrastructure (e.g. pipes and pile foundations) using AE is described in the paper. The monitoring concept employs pre-existing, or newly built, buried steel shell structures as waveguides (e.g. pipes and piles). The propagation of AE through example pipes acting as waveguides has been modelled computationally using the program Disperse. A parametric study is being used to investigate the influence of key variables such as burial depth, surrounding soil type, internal environment, pipe diameter, wall thickness, frequency and mode type upon AE propagation and attenuation. Understanding the propagation and attenuation of AE is of fundamental importance for development of a monitoring strategy and specifically to determine the spacing of sensors along infrastructure elements. The generation of AE due to soil-structure interaction mechanisms is being investigated using a programme of large direct-shear tests of soil against steel plates under a range of conditions (e.g. soil type, plate surface conditions, stress level, strain rate). The aim of the study is to develop a monitoring framework for AE monitoring of buried infrastructure, which requires new understanding of the AE generated by soil-structure interaction, and how this AE attenuates as it propagates to the sensor locations. The principal findings from the research reported here are:

- Attenuation is largely independent of the structural properties of waveguides, assuming the material properties remain constant.
- Attenuation during propagation of the fundamental symmetric and asymmetric Lamb waves within a waveguide buried in soil is largely governed by the properties of the soil, particularly density and stiffness moduli (e.g. acoustic impedance) of the adjacent soils as this controls the reflection and transmission of waves at half-space boundaries.
- Systematic and independent variation of the soil properties (density, Poisson's ratio and Young's modulus) show very similar attenuation behaviours due to their inter-relation and consequent interrelated influence on acoustic impedance although to varying extents.
- Wave mode is important with symmetric and asymmetric Lamb modes displaying both different degrees of attenuation, and attenuation relationships. Generally however, the symmetric mode experiences less attenuation than the asymmetric modes at the frequency-thicknesses of interest. The practical importance of this finding is to understand the relative detected magnitude of the different mode types at different sensor locations.
- Large direct-shear box tests have shown that AE can be used to measure pre- and post-peak shear strength behaviour, which is critical for health monitoring of geotechnical infrastructure. When peak strength has been mobilised, accelerating deformation behaviour takes place which can have catastrophic consequences.

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